Collider signatures of the Gauge-Higgs Dark Matter

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Abstract

A recently proposed $SO(5)\times U(1)$ gauge-Higgs unification model in the Randall-Sundrum warped space contains a very interesting dark matter candidate, the Higgs boson. As a part of the fifth component of a five-dimensional gauge field, the four-dimensional neutral Higgs boson has odd H parity while all the other standard model particles have even parity to all orders in perturbation theory. Based on H parity conserving $WWHH$ and $ZZHH$ vertices, we investigate the collider signatures of Higgs dark matter production associated with a standard model W or Z gauge boson at the LHC and the International Linear Collider (ILC). The final state consists of a W or a Z boson with large missing energy. We found that the level of the signal cross section is quite hopeless at the LHC, while we may be able to identify it at the ILC with polarized electron beams.

I. INTRODUCTION

The presence of cold dark matter (CDM) in our Universe is now well established by a number of observational experiments, especially the very precise measurement of the cosmic microwave background radiation in the Wilkinson Microwave Anisotropy Probe (WMAP) experiment [1]. Though the gravitational nature of the dark matter (DM) is established, we know almost nothing about the particle nature, except that it is, to a high extent, electrically neutral.

One of the most appealing and natural CDM particle candidates is the *weakly interacting massive particle* [2]. It is a coincidence that if the dark matter is produced thermally in the early Universe, the required annihilation cross section times the velocity is about 1 pb. This is exactly the size of the cross sections that one expects from a weak interaction process and that would give a large to moderate production at the LHC. In general, the production of dark matter particles at the LHC gives rise to large missing energy. Thus, the anticipated signature in the final state is high-p_T jets or leptons plus large missing energy.

The most studied dark matter candidate is the neutralino of the supersymmetric models with R parity conservation [3]. In this work, we study a different scenario, the $SO(5)\times U(1)$ gauge-Higgs unification model [4, 5] based on the Randall-Sundrum warped space [6]. The dark matter is the Higgs boson [7], which is a part of the fifth component of a gauge boson field in the model. In such a 5D model, the Higgs boson is the fluctuation mode of the Aharonov-Bohm phase $\hat{\theta}_H$ in the extra dimension [8]. It was shown that at the value of $\theta_H = \pm\pi/2$ the effective potential of the Higgs boson is minimized. Furthermore, the invariance of the effective interactions under $H \to -H$ prohibits triple vertices such as WWH, ZZH, and $\bar{f}fH$, which is true to all orders in perturbation theory. Thus, the Higgs boson is stable and can be a dark matter candidate.

In this model, the interactions of the Higgs boson with the W, Z, and SM fermions are via 4-point vertices. The Higgs boson can be thermally produced in the early Universe via $WW, ZZ, f\bar{f} \to HH$. Like other DM candidates, the drop of the annihilation rate below the universe expansion rate triggered the freeze-out of the Higgs boson as CDM. It was shown in Ref. [7] that the Higgs boson mass needs to be at 70 GeV in order to satisfy the constraint from WMAP.

Focused on 4-point vertices of HHW^+W^- and $HHZZ$, we study the collider signatures

of this dark matter model. Our main process is the production of a pair of the Higgs bosons associated with a W or Z boson. The final state consists of charged leptons plus large missing energy. However, the detection of this signal is very challenging. The signal cross section is generically small due to the $2 \to 3$ process with the weak coupling. In addition, only one single observable particle in the final state provides very limited kinematics, which could be used to reduce the SM background. As shown below, the signal at the LHC is too small to be useful. On the other hand, the International Linear Collider (ILC) with high beam polarization [9] can substantially improve the sensitivity to the signal.

II. EFFECTIVE INTERACTIONS AND RELIC DENSITY

We consider a $SO(5) \times U(1)$ gauge-Higgs unification model in the 5D Randall-Sundrum warped space [4]. The Higgs boson is the fluctuation mode of the Aharonov-Bohm phase $\hat{\theta}_H$ along the fifth dimension, i.e., $\hat{\theta}_H = \theta_H + H(x)/f_H$. The effective interactions of the Higgs boson are

$$\mathcal{L} = V_{\text{eff}}(\hat{\theta}_H) - m_W^2(\hat{\theta}_H) W_\mu^+ W^{-\mu} - \frac{1}{2} m_Z^2(\hat{\theta}_H) Z_\mu Z^\mu, \tag{1}$$

where these mass functions are $m_W(\hat{\theta}_H) = \frac{1}{2} g f_H \sin\hat{\theta}_H$ and $m_Z(\hat{\theta}_H) = \frac{1}{2} g_Z f_H \sin\hat{\theta}_H$. Here g is the weak gauge coupling and $g_Z = g/\cos\theta_W$. The Higgs effective potential $V_{\text{eff}}(\hat{\theta}_H)$ is generated at one loop level. It is finite and cutoff independent as well as leading to finite Higgs boson mass: the gauge hierachy problem does not arise.

Brief comments on the electroweak symmetry breaking are in order here. The electroweak symmetry is preserved at $\theta_H = 0, \pi$, as can be seen in the W and Z boson masses in Eq.(**??**). Hosotani *et.al.* showed that the contributions from the gauge bosons and their KK states do not change the position of the global minimum of θ_H [4]. However, the large but negative contribution from the 5D top quark field turns $V_{\text{eff}}(\hat{\theta}_H)$ upside down, leading to its global minimum at $\theta_H = \pm\pi/2$. In this model, the large Yukawa coupling of the top quark triggers the electroweak symmetry breaking dynamically, and the W and Z gauge bosons and the SM fermions acquire nonzero masses.

At low energy, this model has the SM particles plus one neutral Higgs boson. Since $\mathcal{L}_{\text{eff}}$ in Eq.(1) with $\theta = \pi/2$ is invariant under $H \to -H$, a new H parity emerges under which the Higgs boson has odd parity while all the other SM particles have even parity. This H parity protects the stability of the Higgs boson, making it a CDM candidate, and prohibits triple

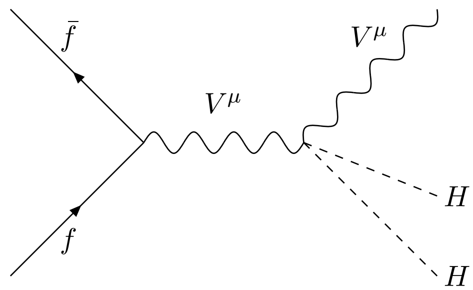

FIG. 1: Feynman diagram for the production of a pair of missing Higgs boson associated with a SM gauge boson V.

vertices of the Higgs boson with the SM particles. Note that the H parity is dynamically generated unlike the R parity in supersymmetric models.

The low energy behavior of the model depends on only two parameters, f_H and m_H. First, f_H is determined by the observed m_W and m_Z, i.e., $f_H \approx 246\,\text{GeV}$. Second, the Higgs boson mass is in principle determined by the matter content of the model. Because of the high model dependence, the Higgs mass has been treated as an unknown parameter. The observed relic density of CDM by WMAP fixes the Higgs boson mass about 70 GeV [7]. Such a low Higgs boson mass does not contradict the LEP bound of the Higgs boson because of the absence of the ZZH coupling. If we further relax the relic density constraint as not overclosing the universe, the Higgs boson mass can be heavier than 70 GeV [7].

We do not consider the 4-point vertices $HH\bar{f}f$, where f is the SM fermion. This vertex comes from the Yukawa coupling, which is proportional to the fermion mass. Although this gives rise to important implications on the direct detection rate, the interaction magnitudes involving $HH\bar{f}f$ are very small, except for the top quark. The process $pp \to t\bar{t}HH$ is also very challenging to observe due to the smaller cross section of the $2 \to 4$ process as well as more difficult identification of top quarks. Therefore, we focus on the 4-point vertices of $HHWW$ and $HHZZ$:

$$\mathcal{L} = -\frac{1}{8} g_Z^2 H^2 Z_\mu Z^\mu - \frac{1}{4} g^2 H^2 W_\mu^+ W^{-\mu}. \tag{2}$$

III. COLLIDER SIGNATURES AT THE LHC

As suggested in Ref. [10], the collider signature of the Higgs DM involves their pair production. Sole pair production via processes such as $WW \to HH$, $ZZ \to HH$, and $gg \to HH$

leaves only missing energy in the final state, which has nothing to be triggered on. We need at least one visible particle to probe the missing transverse energy.

We consider the following production of a pair of Higgs bosons associated with a SM gauge boson $V = W, Z$ at the LHC and ILC: $q(p_1) + \bar{q}(p_2) \to V(q_1) + H(k_1) + H(k_2)$. This process is basically through the Feynman diagram in Fig. 1. The first subprocess that we consider at the LHC is $q\bar{q} \to ZHH$. The spin- and color-averaged matrix element squared is given by

$$\overline{|M|^2}(q\bar{q} \to ZHH) = \frac{1}{4}\frac{1}{N_C}\frac{g_Z^6(g_{qL}^2 + g_{qR}^2)}{4(\hat{s} - m_Z^2)^2}\left(\hat{s} + \frac{4p_1 \cdot q_1\, p_2 \cdot q_1}{m_Z^2}\right) \tag{3}$$

where $N_C = 3$ is the color factor of the quark, $g_{qL} = T_{3q} - Q_q \sin^2\theta_{\rm W}$, $g_{qR} = -Q_q \sin^2\theta_{\rm W}$, and $\hat{s} = (p_1 + p_2)^2$. The differential cross section is

$$d\sigma = \frac{\mathcal{S}}{(2\pi)^5 2\hat{s}}\, \overline{|M|^2}\, dPS_3 \tag{4}$$

where dPS_3 is the 3-body phase space factor and the symmetric factor $\mathcal{S} = 1/2$ is due to a pair of identical Higgs bosons in the final state.

We can consider both leptonic and hadronic decays of the Z boson. The signature in the final state is a reconstructed Z boson with a large missing transverse energy. The irreducible SM background consists of ZZ production with one of the Z bosons decaying into neutrinos. The other reducible backgrounds include Z+jets with the jets lost in the beam pipe, $t\bar{t}$ production with the charged leptons or jets reconstructed at the Z mass while all other particles are undetected. Since the irreducible background is already much larger than our signal, we only include it in our analysis.

The second subprocess that we consider at the LHC is $q\bar{q} \to WHH$. The spin- and color-averaged matrix element squared is given by

$$\overline{|M|^2}(q\bar{q}' \to WHH) = \frac{1}{4}\frac{1}{N_C}\frac{g^6}{8(\hat{s} - m_W^2)^2}\left(\hat{s} + \frac{4p_1 \cdot q_1\, p_2 \cdot q_1}{m_W^2}\right). \tag{5}$$

The differential cross section is that in Eq.(4). We consider both the leptonic and hadronic decays of the W boson. The final state consists of a reconstructed W boson in the hadronic mode or an isolated charged lepton in the leptonic mode, plus large missing transverse energy. Irreducible background consists of WZ production with the Z boson decaying into neutrinos.

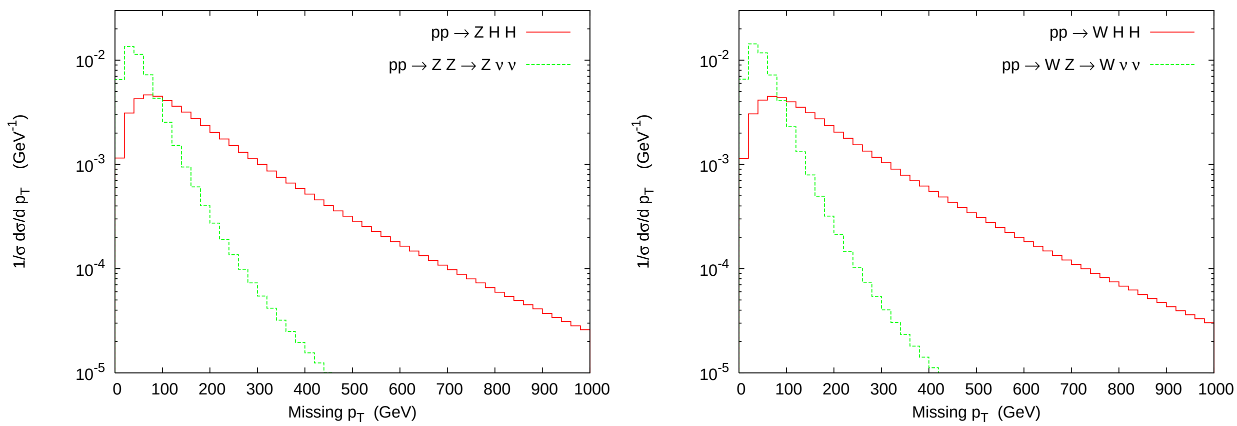

FIG. 2: The *normalized* missing p_T spectrum for (a) ZHH and (b) $W^{\pm}HH$ production at the LHC, with the corresponding background $ZZ \to Z\nu\bar{\nu}$ and $WZ \to W\nu\bar{\nu}$. The impose cut is $|y(W/Z)| < 2$.

In Figs. 2 (a) and (b), we compared, with the corresponding backgrounds, the spectrum of the missing transverse momentum for the ZHH and WHH signals, respectively. We have assumed that the Z or the W boson can be reconstructed. The signal and the background have been normalized, since the background is 3 orders of magnitude larger than the signal. Applying a strong cut on the missing $p_T > 100\,\text{GeV}$, we arrive at the signal-background ratio shown in Table I. Larger p_T cut would further hurt our signal. Even with a possible luminosity of 100 fb^{-1} the signal-background significance is still very low to afford any positive identification of the model.

TABLE I: The cross section in fb for the signals ZHH and $W^{\pm}HH$ and the corresponding backgrounds $ZZ \to Z\nu\bar{\nu}$ and $WZ \to W\nu\bar{\nu}$ at the LHC. The applied cuts include $|y(Z/W)| < 2$ and $\not{p}_T > 100$ GeV.

ZHH	$ZZ \to Z\nu\bar{\nu}$	$W^{\pm}HH$	$WZ \to W\nu\bar{\nu}$
0.2 fb	370 fb	0.4 fb	390 fb

IV. SIGNATURES AT THE ILC

The advantages of the ILC with electron and positron beams include (i) known initial energy in the collision level, and (ii) capability of polarization in the electron and positron beams. With known initial energy we can calculate the mass of any particle(s) missing

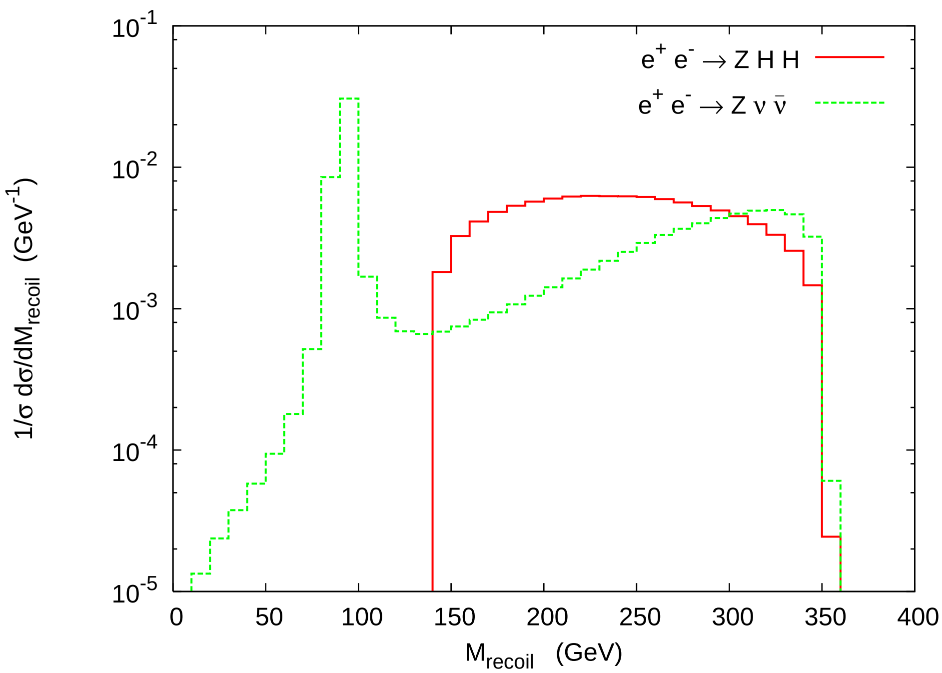

FIG. 3: Normalized recoil mass spectrum for $e^-e^+ \to ZHH$ and $e^-e^+ \to Z\nu\bar{\nu}$, which includes three flavors of neutrinos, at $\sqrt{s} = 0.5$ TeV. Imposed cuts include $|\cos\theta_Z| < 0.8$ and $p_{TZ} > 100$ GeV.

by measuring the energy of the visible particles—the method of recoil mass. In the signal process $e^-e^+ \to ZHH$, the Z boson is measured by the momenta of the two charged leptons or the two jets while the two Higgs bosons are missing. We construct the recoil mass by

$$m_{\rm recoil} = m_{HH} = \left[s + m_Z^2 - 2\sqrt{s}E_Z\right]^{1/2} , \qquad (6)$$

where m_{HH} is the invariant mass of the HH system. Thus, the recoil mass spectrum will start at $2m_H$ and be continuous with no peak structure. On the one hand, the recoil mass spectrum of the background process $e^-e^+ \to \sum_{i=e,\mu,\tau} Z\bar{\nu}_i\nu_i$ is very different. For $Z\bar{\nu}_\mu\nu_\mu$ and $Z\bar{\nu}_\tau\nu_\tau$, the dominant production mechanism is via $e^-e^+ \to ZZ \to Z\bar{\nu}\nu$: a sharp peak in the recoil mass distribution emerges right at the mass m_Z. Another mechanism is the Z boson radiated off a leg in $e^+e^- \to \bar{\nu}\nu$, but it is very small. However, $Z\bar{\nu}_e\nu_e$ production has additional major production mechanism mediated by a t-channel W boson. This yields a continuous spectrum as well as a broad peak toward the high end in the $m_{\rm recoil}$ distribution. We show the normalized recoil mass spectrum in Fig. 3.

It is clear in Fig. 3 that we can use a recoil mass cut to remove the background due to the Z peak. However, the continuous SM background with the broad peak toward high end is

still very large, thus reducing the sensitivity of our signal. Since this continuous background mainly comes from the Feynman diagrams with a W boson exchange, we can use right-hand polarized electron beam and/or left-hand polarized positron beam to largely reduce the background. The remaining contribution comes from those with Z boson exchange. On the other hand, the signal receives compatible contributions from left-handed and right-handed electrons according to the size of $(g_{eL})^2 \approx (-0.27)^2$ and $(g_{eR})^2 \approx (0.23)^2$, respectively. In Table II, we show various cross sections of the signal and the corresponding background, using cuts and realistic polarized beams. Note that both signal and background have zero cross sections when the electron and positron have the same helicities, $(-,-)$ and $(+,+)$.

TABLE II: The cross section in fb for the signals $e^-e^+ \to Z^{(\mathrm{vis})}HH$ and the corresponding backgrounds $e^-e^+ \to Z^{(\mathrm{vis})}\nu\bar{\nu}$ at a 0.5 TeV ILC, using polarized beams. Here $Z^{(\mathrm{vis})}$ denotes the Z boson considering only its visible decay (a branching ratio of 0.8 has been multiplied). Imposed cuts include $|\cos\theta_Z| < 0.8$, $p_{TZ} > 100$ GeV, and $m_{\mathrm{recoil}} > 140$ GeV. The significance $S/\sqrt{B}$ is based on the ILC luminosity of 1000 fb^{-1}.

P_{e^-}	P_{e^+}	$\sigma(e^-e^+ \to Z^{(\mathrm{vis})}\nu\bar{\nu})$	$\sigma(e^-e^+ \to Z^{(\mathrm{vis})}HH)$	$\frac{S}{\sqrt{B}}$
+1	−1	3.8 fb	0.14 fb	2.2
−1	+1	200 fb	0.18 fb	0.4
0	0	52 fb	0.08 fb	0.3
0.8	−0.6	6.8 fb	0.10 fb	1.2

V. CONCLUSIONS

In the $SO(5)\times U(1)$ gauge-Higgs unification model based on the Randall-Sundrum warped spacetime, the Higgs boson is a part of the fifth component of a higher-dimensional gauge field. Because of the invariance of the effective Lagrangian under $H \to -H$, this model accommodates the H parity, under which the Higgs field is odd while all the other SM particles are even. The triple vertices of HWW, HZZ, and $H\bar{f}f$ vanish. The very SM Higgs boson is the dark matter candidate. At low energy, this model is highly constrained as it has only one free parameter, the mass of the Higgs boson. The WMAP data on the relic density constrain $m_H \simeq 70\,\mathrm{GeV}$.

Collider production of the Higgs boson must come in pairs. The most direct way to detect is the associated production with a W or Z boson. The collider signature is the W/Z boson with a large p_T missing. We have shown that at the LHC the SM production of WZ and ZZ simply overwhelms the signal even with quite strong kinematic cuts. Although the Higgs boson could also be pair produced in WW fusion or gg fusion, the detection of the merely missing energy signal would be much more difficult.

On the other hand, we have shown that the whole situation substantially improves at the ILC with polarized beams. The kinematic cut on the recoil mass can suppress the $e^-e^+ \to ZZ \to Z\nu\bar{\nu}$ background, and a right-hand polarized electron beam can dramatically reduce the W-mediated $e^-e^+ \to Z\bar{\nu}_e\nu_e$ background. We can therefore do an event counting to measure the significance level of the signal.

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